THE EFFECT OF FEED WATER TYPE AND FEED FLOW RATE ON THE PERFORMANCE OF REVERSE OSMOSIS FOR WATER DESALINATION

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ABSTRACT

This study was carried out to evaluate the effect of water type and feed flow rate on the performance of reverse osmosis system which was used for water desalination. Two types of water included well water (9.6 dS.m^{-1}) and drainage water (4.25 dS.m^{-1}) and three levels of feed flow rate included 4.2, 4.8 and 5.4 m^3 h^{-1} were used in this experiment. Productivity, recovery ratio, specific energy, electrical conductivity and rejection ratio were measured in this experiment. Split plot under complete randomize block design (CRBD) with three replicates was used. It was found that the use of drainage water (EC = 4.25 dS.m^{-1}) led to obtain higher productivity (3.04 m^3 h^{-1}) , higher recovery ratio (63.91%) and higher rejection ratio (97.42 %) and led to obtain lower specific energy (2.56 kW m-3) and lower electrical conductivity (0.109 dS.m^{-1}) . It was also found that the use of higher feed flow rate (5.4 m^3 h^{-1}) led to obtain higher productivity (2.53 m^{3}h^{-1}) and higher rejection ratio (97.06 %) and led to obtain lower recovery ratio (46.98%) , lower specific energy (3.5 kWm-^{3}) and lower electrical conductivity (0.218 dS.m^{-1}). It was found that The interaction between lower feed water salinity (drainage water) and higher feed flow rate 5.4 dS.m^{-1} led to obtain the highest productivity 3.21 m^3 h^{-1}, lowest specific energy 2.45 kW m-3 , lowest electrical conductivity 0.101 dS.m^{-1} and highest rejection ratio 97.60 % while the interaction between lower feed water salinity (drainage water) and lower feed flow rate 4.2 m^3 h^{-1}led to highest recovery ratio 68.75 % .

Keywords: Productivity, recovery ratio, specific energy, electrical conductivity and rejection ratio.

***The research is part of the second researcher theses.**

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تأثير نوع مياه التغذية ومعدل الجريان على إداء منظومة التنافذ العكسي لتحلية المياه

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المستخلص

نفذت هذه التجربة لتقييم تأثير نوع مياه التغذية ومعدل الجريان على أداء منظومة التنافذ العكسي والتي أستخدمت لغرض تحلية المياه حيث تم أستخدام نوعين من المياه الاول مياه بئر (9.6 ديسي سيمنز / متر) والثاني مياه بزل (4.25 ديسي سيمنز/ متر) وتم أستخدام ثلاثة مستويات من معدل الجريان والتي تضمنت 4.2 ، 4.8 و 5,4 م3 / ساعة. وتم قياس الانتاجية ، نسبة الاستخلاص ، الاستهلاك النوعي للطاقة، الأيصالية الكهربائية للمياه المنتجة و نسبة رفض الاملاح . وتم أستخدام القطاعات المنشقة بأستخدام القطاعات الكاملة المعشاة وبثلاث مكررات .كما تم أستخدام أقل فرق معنويي LSD للمقارنة بين المتوسطات .وأشارت النتائج الى أن أستخدام مياه البزل (4.25 ديسي سيمنز / متر) أدى الى الحصول على أعلى أنتاجية (3.04 م^3/ ساعة)، أعلى نسبة أستخلاص (63.91 %)، أعلى نسبة رفض للاملاح (97.42 %) ، أقل أستهلاك نوعي للطاقة (2.56 كيلو واط / م^3) وأقل توصيل كهربائي للمياه المنتجة (0.109 ديسي سيمنز / متر). كما وجد بأن أستخدام معدل الجريان (5.4 م^3/ساعة) أدى االى الحصول على أعلى أنتاجية (2.53 م3/ساعة) ، أعلى نسبة رفض للاملاح (97.06 %) والحصول على أقل نسبة أستخلاص (46.98 %) وأقل أستهلاك نوعي للقدرة (3.5 كيلو واط / م3) وأقل إيصالية كهربائية للمياه المنتجة (0.218 ديسي سيمنز / متر) . ووجد أن ألتداخل بين مياه البزل (4.25 ديسي سيمنز / متر) وأعلى معدل جريان أدى الى الحصول على أعلى أنتاجية (3.21 م3/ساعة)، أقل أستهلاك نوعي للطاقة (2.45 كيلو واط / م3) ، أقل توصيل كهربائي للمياه المنتجة (0.101 ديسي سيمنز / م)، أعلى نسبة رفض للاملاح (97.6 %) بينما التداخل بين مياه البئر (9.6 ديسي سيمنز / متر) و أقل معدل جريان 4.2 م3/ساعة أدى الى الحصول على أعلى نسبة أستخلاص (68.75 %).

الكلمات الدالة: الانتاجية ، نسبة الاستخلاص ، الاستهلاك النوعي للطاقة ، الأيصالية الكهربائية للمياه المنتجة و نسبة رفض الاملاح

***البحث جزء من رسالة ماجستير للباحث الثاني.**

INTRODUCTION

The desalination of salty well water and drainage water is an important option to provide new resource of irrigation water. Reverse Osmosis (RO) is one of the most important methods of water desalination. For agricultural uses, reverse osmosis is the preferred desalination technology due to the cost reductions driven by improvements in membranes in recent years. Al zubadi (3) illustrated that the reverse osmosis is a scientific process to reverse the physical phenomena which called osmosis. (Osmosis is a natural process where water flows through a semi-permeable membrane from solution with low concentration of dissolved solids to solution with high concentration of dissolved solids). Reverse osmosis allows separation of salt from solution whenever a pressure greater than the osmotic pressure of the solution is applied through semi-permeable membrane (7). In reverse osmosis system feed water passes tangentially over the membrane surface. Water and some dissolved solids pass through the membrane while the majority of dissolved solids and some water do not pass through the membrane. Hence, one feed stream is separated into two exit streams. The solution passing through the membrane surface (permeate) and the remaining concentrate stream (Brine). The rejected particles are swept away by the concentrate stream figure (1) illustrate Schematic of a simple reverse osmosis system. 1. Feed water. 4. Reverse osmosis membrane. 2. High pressure pump. 5. Rejected water (brine). 3. Pressured feed water. 6. Produced water (permeate).

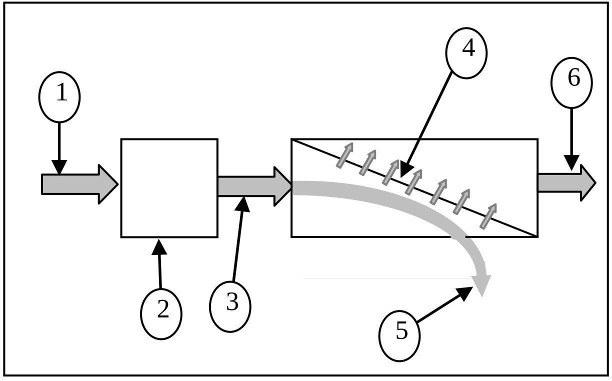

Figure 1. Schematic of a simple reverse osmosis system (18)

1. Feed water. 4. Reverse osmosis membrane
2. High pressure pump. 5. Rejected water (brine).
3. Pressured feed water. 6. Produced water (permeate)

-In reverse osmosis The quantity of pure water that passes through the membrane during reverse osmosis is a function of the difference between the applied pressure and the osmotic pressure of the saline solution (6, 19) illustrated that when the feed concentration increased , the osmotic pressure across the membrane will increase and the product rate would be decreased . Lyster and Cohen (13) mentioned that the rejection of salt ions at a membrane surface in cross-flow reverse osmosis results in increased solute concentration near the membrane surface. This phenomenon is called “concentration Polarization” (11). Concentration polarization is one of the primary reasons for flux decline (8). It is undesirable phenomenon which results in the increase of the osmotic pressure at the membrane wall and consequently, a reduction in the product flux and the membrane rejection (2 ,7) mentioned that increasing feed flow rate would increase turbulence and reduces the thickness of the high concentration layer near the membrane surface . Higher feed flow rate causes greater water flux since it minimizes a concentration polarization by changing the mixing in the system (15, 17). said that the feed with low salt concentration water produced higher recovery ratios compared to that produced by high feed salinityl (22). found that increasing feed flow rate will result in a reduction in recovery. Macharg, et al (14) found that the Feed water salinity has the most significant impact on power consumption (12). said that at the higher the concentration of salts, the more important the osmotic pressure becomes and therefore the greater the energy required (21). said that as the TDS of feed water increases, the required operating pressure increases. Therefore, more energy is expended for making the same amount of water (21) also mentioned that the feed flow rate of an RO system will directly affect the product flow rate and the specific energy (kW m-3) of the product (9). indicated that the permeate concentration essentially increases with the increase in the feed concentration (4). illustrated that the reason why the product or the permeate contains solute (that ought to be removed) is that the solute has broken through the membrane surface along with the product water. It may be said that as long as the solute stays away from the membrane surface, only water will pass through into the product side and the permeate will be solute-free; However, it is not possible to exclude the solute from contacting the membrane surface; hence, it is always liable to break through (6). conducted that the effect of feed concentration has the greatest effect on the solute concentration in product among other variables (1). mentioned that the concentration of ions in the product solution decreases with increasing feed flow rate and increasing feed flow rate would improve the separation by a decrease in the concentration of ions in the product (20) found that the different ions are not rejected equally by the same RO membrane. Usually the larger the ions and the higher their electrical charge the better rejected they are. This means for example that divalent ions such as calcium and magnesium will be rejected better than monovalent ions such as sodium and chloride (16) mentioned that with mixtures of salts in solution, the rejection of a single ion is influenced by its relative proportion in the mixture. Therefore the experiment was conducted to evaluate the feed water types and feed flow rate on the performance of reverse osmosis.

MATERIALS AND METHODS

The experiment was conducted to evaluate the effect of water type and feed flow rate on the performance of reverse osmosis. Two type of water included well water and drainage water (Table 1) and three levels of feed flow rate included 4.2, 4.8 and 5.4 m3/hour were used in this experiment. Split plot under complete randomize block design (CRBD) with three replicates was used. Least significant difference (LSD) was used to compare among treatments at 0.05 probabilities. The main parts of reverse osmosis unit are: Feed pump, Multimedia pressure filter, Cartridge filters, High pressure pump, Membrane assembly unit (Membrane assembly unit consisted of pressure vessel and membrane elements. Two spiral-wound membrane elements (Dow FILMTEC BW – 365) connected in series were installed in the pressure vessel, Flow meters, valves, Pressure gauges and permeate tank.

Table 1. Well and drainage water analysis.

	Well Water	Drainage Water
PH	**8.23**	**7.8**
EC (dS.m-1)	**9.6**	**4.25**
Na (meq L-1)	**50.6**	**7.8**
K ((meq / l)	**0.158**	**0.238**
Mg (meq L-1)	**25.4**	**16.18**
Ca (meq L-1)	**19.2**	**18**
HCO_3 (meq L-1)	**3.4**	**1.2**
CO_3 (meq L-1)	**0.5**	**0**
Cl (meq L-1)	**36.8**	**18.6**
NO_3 (meq L-1)	**0.24**	**0.009231**
SO_4 (meq L-1)	**50.2**	**21**
PO_4 (meq L-1)	**0.29**	**0.06**

The following variables were studied:

1. Productivity ($m^3\ h^{-1}$)**:** productivity is the amount of water (m^3) which produced per hour. The productivity was obtained from the reading of the product flow meter.

2. Recovery ratio %: Recovery ratio is the percentage of the feed water that is recovered in the desalination process as fresh product water. The recovery ratio was calculated from the following equation (10):

$$Recovery\,\% = \frac{\text{Permeate flow}}{\text{Feed flow}} \times 100$$

3. Specific energy: The specific energy is the energy consumption per volume of produced permeate. The specific energy was calculated according to the following equation (18):

$$\text{Specific energy} = \frac{\text{Input power (kW)}}{\text{product flow } (m^3)}$$

4. Electrical Conductivity (EC) : Electrical conductivity of produced water (permeate) was measured by electrical conductivity meter.

5. Rejection ratio (salt rejection): Salt rejection is a measure of how well a membrane element rejects the passage of dissolved ions. The salt rejection was calculated by the following equation (5):

$$\text{Rejection raio} = \left(1 - \frac{\text{Permeate conductivity}}{\text{Feed water conductivity}}\right) \times 100$$

The permeate conductivity and feed water conductivity were measured using electrical conductivity meter.

RESULTS AND DISCUSSION

Table 2 Shows that there was a significant effect of feed water type on the productivity of reverse osmosis system. The higher productivity (3.04 m3 h-1) was obtained by using drainage water while the lower productivity (1.67 m3 h-1) was obtained using well water. This result obtained due to the well water (EC = 9.6 dS.m-1) had higher osmotic pressure then drainage water (EC = 4.25 dS. m-1). Increase osmotic pressure of feed water would reduce driving force for water through the membrane. This result agreed with (6, 8) results. The same table also shows a significant effect of feed flow rate on the productivity of reverse osmosis system. The higher productivity (2.53 m3 h-1) was obtained by using 5.4 m3 h-1 while the lower productivity (2.18 m3 h-1) was obtained by using 4.2 m^3 / h .This result due to feed flow rate has direct effect on the concentration of high concentrated boundary layer which might accumulate at membrane surface. Increasing feed flow rate would increase turbulence and reduces the thickness of this concentrated layer by promoting good mixing of the bulk feed solution with the solution near the membrane surface. This would reduce the osmotic pressure near the membrane surface and allow more water to pass through the membrane. This result agreed with Madwar and Tarazi (15) and Al-Busaidi (2) results. Table 2 also shows that there was a significant effect of interaction between feed water type and feed flow rate on the productivity of reverse osmosis. The higher productivity (3.21 m3 h-1) was obtained by using drainage water (4.25 dS.m^{-1}) and (5.4 m3 h-1) feed flow rate . While the lower productivity (1.48 m3 h-1) was obtained by using well water (9.6 dS.m^{-1}) and (4.2 m3 h-1) feed flow rate . The reason for this result due to both decreasing feed water salinity and increasing feed flow rate would reduce salt concentration at feed side of the membrane. When the salinity of feed water increase more salt ions would be rejected by the membrane. These ions can accumulate at the membrane surface and increase the gradation between the concentration of boundary layer and bulk of the solution. Increasing feed flow leads to decreasing the concentration of boundary layer by providing good mixing of the bulk feed solution with the solution near the membrane surface. So that reducing salinity and increasing feed flow rate would decrease the concentration of salt ions near the membrane surface. As the concentration of salt ions at the membrane surface decreases the osmotic pressure would decreases too. So that the productivity of reverse osmosis unit increase as the feed water salinity decreases and feed flow rate increases.

Table 2. effect of feed water type and feed flow rate on the Productivity (m3 h-1) of reverse osmosis unit.

Water Type	Feed Flow Rate (m3 h-1)			Water Type Average
	4.2	4.8	5.4	
Drainage Water	2.88	3.05	3.21	3.04
Well Water	1.48	1.68	1.86	1.67
LSD = 0.05	0.0244			0.0271
Feed Flow Rate Average	2.18	2.36	2.53	
LSD = 0.05	0.0175			

Table 3 shows a significant effect of feed water salinity on the recovery of reverse osmosis system. The higher recovery ratio (63.91%) was obtained using drainage water while the lower value (35.01%) was obtained using well water. This result due to the differences between osmotic pressure of two solutions. Increasing feed water salinity would decrease productivity and recovery of reverse osmosis system. This result agreed with Sassi and Mujtaba (17) result. Table 3 also shows a significant effect of feed flow rates on the recovery of reverse osmosis system. The higher recovery (52.09 %) was obtained by the lower feed flow rate while the lower recovery (46.98 %) was obtained by higher feed flow rate. Increasing feed flow rate would lead to decreasing recovery. This is due to the inverse relation between recovery and feed flow rate. This result agreed with the result which was obtained by Zhou et al (22) result. Table 3 also shows that there was a significant effect of interaction between feed water type and feed flow rate on the recovery ratio. The higher recovery ratio (68.75 %) was obtained by drainage water and (4.2 m3 / hour) feed flow rate and the lower recovery ratio (34.52 %) was obtained by well water and (5.4 m3 / hour) feed flow rate . This result due to the recovery ratio which is directly proportional to the productivity of reverse osmosis system and the inverse proportional to the feed flow rate. So that increase productivity would lead to increase the recovery ratio while increase feed flow rate would reduce the recovery ratio.

Table 3. effect of interaction between feed water type and feed flow rate on the recovery ratio of reverse osmosis unit.

Type	Feed Flow Rate (m3 h-1)			Water Type Average
	4.2	4.8	5.4	
Drainage Water	68.75	63.54	59.45	63.91
Well Water	35.44	35.05	34.52	35.01
LSD = 0.05	0.5893			0.633
Feed Flow Rate Average	52.09	49.29	46.98	
LSD = 0.05	0.4316			

Table 4 shows a significant effect of feed water type on the specific energy. The higher specific energy (5.07 kW m-3) was obtained using well water while the lower specific energy (2.56 kW m-3) was obtained using drainage water. This result was obtained due to increasing feed water salinity led to increase osmotic pressure. As the osmotic pressure increase the water flux through the membrane decreases and the power consumption increases. These results agreed with Kumar and Saravanan (11) and Macharg, et al (14) results. Table 4 also shows a significant effect of feed flow rate on the specific energy. The higher specific energy (4.16 kW m-3) was obtained using lower feed flow rate (4.2 m3 / hour) while the lower specific energy (3.5 kW m-3) was obtained using higher feed flow rate (5.4 m3 / hour).This result due to inverse relation between productivity and specific energy. Increasing productivity of reverse osmosis (due to increase feed flow rate) led to decrease specific energy. This result agreed with Watson et al (21) result. Table 4 shows a significant effect of interaction between feed water type and feed flow rate on the specific energy. The higher specific energy (5.65 kW m-3) was obtained using well water and (4.2 m^3/ hour) feed flow rate , while the lower specific energy (2.45 kW m-3) was obtained using lower feed water salinity (drainage water) and higher feed flow rate (5.4 m^3/hou). It is obvious that the specific energy is directly proportional to power consumption and inversely proportional to productivity. Both feed water salinity and feed flow rate effect the power consumption and productivity of reverse osmosis unit. Increase feed water salinity led to increase the osmotic pressure of feed water. As the osmotic pressure of feed water increase more energy will be required to overcome osmotic pressure. On the other hand decreases feed water salinity and increases feed flow rate would increase productivity of reverse osmosis unit. As a result the specific energy increased with higher feed water salinity (9.6 dS.m^{-1}) and lower feed flow rate (4.2 m^3/h).

Table 4. the effect of feed water type, feed flow rate on the specific energy (kW m-3).

Water Type	Feed Flow Rate (m3 h-1)			Water Type Average
	4.2	4.8	5.4	
Drainage Water	2.67	2.56	2.45	2.56
Well Water	5.65	5.02	4.55	5.07
LSD = 0.05	0.2015			0.2408
Feed Flow Rate Average	4.16	3.79	3.5	
LSD = 0.05	0.0494			

Table 5 shows a significant effect of feed water type on the electrical conductivity of produced water. The higher electrical conductivity (0.385 dS.m-1) was obtained using higher feed water salinity (well water) while lower electrical conductivity (0.109 dS.m^{-1}) was obtained using lower feed water salinity (drainage water). This result due to the salts flux through the membrane increased when the salt concentration of feed water increased (more salt ions had broken through the membrane surface). These results agreed with Khalaf (9) and Arcadio and Gregoria (4) results. Table 5 shows a significant effect of feed flow rates on electrical conductivity of permeate. The higher electrical conductivity (0.277 dS.m-1) was obtained using (4.2 m3/hour) feed flow rate while lower electrical conductivity (0.218 dS.m-1) was obtained using (5.4 m3/hour). This result due to Increasing feed flow rate which would reduce accumulation of salts at the membrane surface by providing good mixing of concentrated boundary layer with the bulk of solution. Decreasing salt concentration at the membrane surface led to decreasing salts ion which pass through the membrane. This result agreed with Ahmed zeki et al (1) results. Table 5 shows that there is a significant effect of interaction between feed water type and feed flow rate on the electrical conductivity of permeate. The higher electrical conductivity (0.438 dS.m^{-1}) was obtained using higher feed water salinity (well water) with using lower feed flow rate (4.2 m3 h-1) while the lower electrical conductivity (0.101 dS.m-1) was obtained using lower water salinity (drainage water) with using higher feed flow rate (5.4 m3 h-1) . This result due to the increase of salt ions at feed side of the membrane which would lead to increase the amount of salt ions that can break through the membrane. It is obvious that both feed water type and feed flow rates effect the concentration of water at feed side of the membrane (especially at the boundary layer near the membrane surface) . Both increasing of salt concentration and decreasing feed flow rate would cause increasing concentration of boundary layer. So that (at constant pressure) the concentration of boundary layer will be at the maximum value with using higher feed water salinity and lower feed flow rate. Increasing concentration of boundary layer will increase the quantity of ions which can pass through the membrane. So that the electrical conductivity of permeate would increasing with increasing feed water salinity and decreasing feed flow rates.

Table 5. the effect of water type and feed flow rate on the electrical conductivity (dS.m^{-1}) of desalinated water.

Water Type	Feed Flow Rate (m3 h-1)			Water Type Average
	4.2	4.8	5.4	
Drainage Water	0.116	0.108	0.101	0.109
Well Water	0.438	0.382	0.334	0.385
LSD = 0.05	0.0079			0.01
Feed Flow Rate Average	0.277	0.245	0.218	
LSD = 0.05	0.0045			

Table 6 shows a significant effect of feed water type on the rejection ratio. The higher rejection ratio (97.43 %) was obtained using drainage water (EC 4.25 dS/m-1) while lower rejection ratio (95.99 %) was obtained using well water (EC 9.6 dS/m^{-1}). Increase feed water salinity means that more salts ion can pass through the membrane. At the same time, it also obvious that the salt rejection not only affected by the feed water salinity but also affected by feed water composition (feed water chemistry). Not all ions are rejected equally by the same RO membrane. Generally the divalent ions (such as calcium and magnesium) are rejected better than mono-valent ions (such as sodium and chloride). So that increasing the ratio of mono-valent to divalent ions in the feed water would decrease the rejection ratio of reverse osmosis system. These results agreed with Richardson et. al (16) and Voutchkov (20) results. Table 6 also shows a significant effect of feed flow rate on rejection ratio of reverse osmosis system. . The higher rejection ratio (97.06 %) was obtained using higher feed flow rate (5.4 m3/hour) while lower rejection ratio (96.34 %) was obtained using lower feed flow rate (4.2 m3/hour). This result due to the direct effect of feed flow rate on the concentration of boundary layer. Increasing feed flow rate will provide turbulence flow and reduce the concentration of boundary layer. So that the rejection ratio increase with increasing feed flow rate. These results agreed with Ahmedzeki et al (1) results. Table 6 shows a significant effect of interaction between feed water type and feed flow rate on the rejection ratio (Salt rejection). The higher rejection ratio (97.60 %) was obtained using drainage water and higher feed flow rate (5.4 m3/ hour) while the lower rejection ratio (95.44 %) was obtained using well water and lower feed flow rate (4.2 m^3/hour). This result due to the rejection of salts would be affected by the feed water composition and salinity changes. As the different ions are not rejected equally by the same RO membrane. Usually the divalent ions such as calcium and magnesium will be rejected better than monovalent ions such as sodium and chloride. Also with mixtures of salts in solution, the rejection of a single ion is influenced by its relative proportion in the mixture. So using well water which had higher concentration of monovalent ions (Such as sodium and chloride) led to increase the amount of ions which can pass through the membrane. At the same time increase feed water salinity also effects on the salt rejection. Increase feed water salinity means that more salt ions can pass through the membrane. The amount of salt ions which can pass through the membrane directly related to the salt concentration of feed side of the membrane. It is also obvious that both feed water concentration and feed flow rate have an effect on the concentration of salt ions at feed side of the membrane. So that the salt rejection would affected by the changes of feed water type and feed flow rates.

Table 6. the effect of water source feed flow rate and operating pressure on the rejection ratio(%)

Water Type	Feed Flow Rate (m3 h-1)			Water Type Average
	4.2	4.8	5.4	
Drainage Water	97.25	97.44	97.60	97.42
Well Water	95.44	96.01	96.52	95.99
LSD = 0.05	0.164			0.205
Feed Flow Rate Average	96.34	96.72	97.06	
LSD = 0.05	0.051			

Therefore, it can be concluded that the reverse osmosis can used successfully to desalinate well water and drainage water .Using lower feed water salinity (drainage water (4.25 dS.m^{-1}) and using higher feed flow rate (5.4 m3 h-1) to obtain the best performance.

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